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MECHANICAL DISPERSION IN FRACTURED CRYSTALLINE ROCK SYSTEMS

by

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ABSTRACT

This report is part of a larger study which compiles and evaluates the hydrogeologic parameters describing the flow of groundwater and transport of solutes in fractured crystalline rocks. This report describes the processes of mechanical dispersion in fractured crystalline rocks, and compiles and evaluates the dispersion parameters determined from both laboratory and field tracer experiments. The compiled data show that extrapolation of the reliable test results performed over intermediate scales (10's of m and 10's to 100's of hours) to larger spatial and temporal scales required for performance assessment of a nuclear waste repository in crystalline rock is not justified. The reliable measures of longitudinal dispersivity of fractured crystalline rock are found to range between 0.4 and 7.8 m.

RÉSUMÉ

Le présent rapport fait partie d'une recherche plus vaste destinée à compiler et à évaluer les paramètres hydrogéologiques qui déterminent l'écoulement des eaux souterraines et le transport des solutés dans les roches cristallines fracturées. Nous décrivons les processus de dispersion mécanique dans les roches cristallines fracturées et nous procédons à une compilation et à une évaluation des paramètres de la dispersion déterminés en laboratoire et sur le terrain à l'aide de marqueurs. Les données compilées montrent que l'extrapolation à partir des résultats fiables des essais menés à des échelles intermédiaires (dizaines de mètres et dizaines à centaines d'heures) pour obtenir des données correspondant aux échelles spatiales et temporelles plus vastes nécessaires à l'évaluation du rendement d'un dépotoir de déchets nucléaires dans un massif cristallin, n'est pas justifiée. Les mesures fiables de la dispersivité longitudinale de la roche cristalline fracturée varient en effet de 0, 4 à 7, 8 m.

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1.0 INTRODUCTION

1.1 BACKGROUND

A fundamental concept underlying the Canadian nuclear waste disposal program is the isolation of these wastes through deep underground disposal. The Canadian program has centred on the use of crystalline rock masses as the candidate rock type. The focus of the program, like most other nuclear waste disposal programs, is geared towards evaluating the performance of a repository located in such a rock mass over its life span. The purpose of such an evaluation (or performance assessment) is to quantify the impact that the construction and operation of such a facility would have on the environment (in general) and on humans in particular. The most likely mechanism which would be responsible for the release of radioactive material would be by the leaching and dissolution of the inventory by groundwater coupled with the subsequent movement through the groundwater system to the accessible environment. In order to evaluate the risk posed to the human population, it is essential that the factors controlling the movement of solute and groundwater in fractured crystalline rocks be well understood. For this reason, the Atomic Energy Control Board (AECB) has commissioned a study to identify and review hydrogeologic properties pertinent to the flow of groundwater in the plutonic rock environments being considered for disposal of nuclear waste by Atomic Energy of Canada Ltd. (AECL). The current study is an extension of the initial study and is intended to review and evaluate parameters associated with the mechanical dispersion of solute in crystalline rock systems.

1.2 SCOPE OF WORK

The current study forms one particular aspect of a larger study being conducted by INTERA Technologies Ltd. (formerly GTC Geologic Testing Consultants Ltd.) for AECB. The portion of the study

described in this report involves the identification and evaluation of mechanical dispersion properties in fractured crystalline rock environments. More specifically the current study is charged with:

- identifying those parameters which determine the dispersion in a hydrogeologic system as well as factors which may influence these parameters;
- describing and evaluating methods of determining dispersion parameters and discussing problems/difficulties associated with these methods;
- searching for and compiling all information related to the dispersion of solutes in fractured crystalline rock systems including the scale and method of data acquisition.

2. DISPERSION

2.1 DEFINITION

A non-reactive or inert solute moving through a hydrogeological system is subject to two processes which tend to reduce the magnitude of any spatial concentration gradients that may exist. These tw processes are often referred to as molecular diffusion and mechanical dispersion. The molecular diffusion of a solute within a hydrogeological system is dependent upon both the properties of the solute (e.g., internal energy, molecular diameter) and the properties of the medium (e.g., tortuosity and porosity). Mechanical dispersion, on the other hand, represents the solute mixing that arises due to the existence of velocity variations within the hydrogeologic system. These velocity variations include those that arise within an individual fracture or pore (due to viscous nature of the fluid and roughness of fracture/pore walls) or on a larger scale (due to the presence of heterogeneities and different flow paths). Figure 2.1 schematically presents the various factors contributing to mechanical dispersion. Conceptually, mechanical dispersion can be distinguished from molecular diffusion as being dependent upon velocity variations (i.e., mechanical dispersion is zero when the velocity is zero). The effect of dispersion upon solute transport can be seen in Figure 2.2 which presents successive breakthrough curves for both dispersed and non-dispersed (i.e., plug flow) solute.

There has been a general tendency to treat mechanical mixing in an analogous manner to molecular diffusion. This approach is often referred to as the Fickian treatment of mechanical dispersion, since it assumes that the dispersion may be described using Ficks laws of diffusion. The impetus for a Fickian approach stems primarily from the ease with which mechanical dispersion can be incorporated into the advection-diffusion (subsequently advection-dispersion) equation. The founding work by Taylor (1953) and Aris (1956) demonstrated the applicability of the advection-dispersion equation in describing the dispersion of solute flowing in a tube.

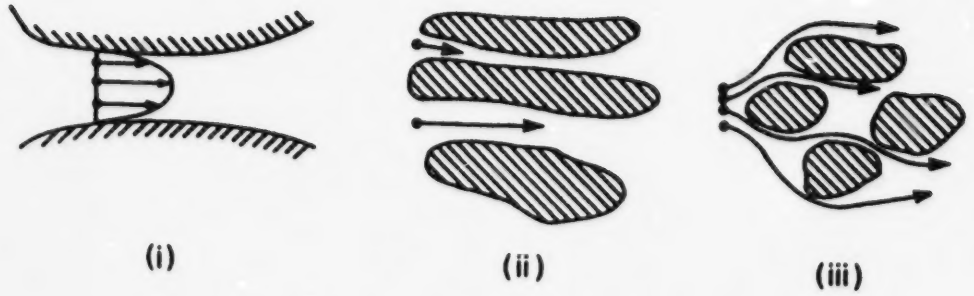

Figure 2.1 Factors Contributing to Mechanical Dispersion
(i) velocity distribution in a single pore/fracture
(ii) varying cross-sectional area of different streamlines
(iii) different pathline lengths
(after Gillham and Cherry, 1982)

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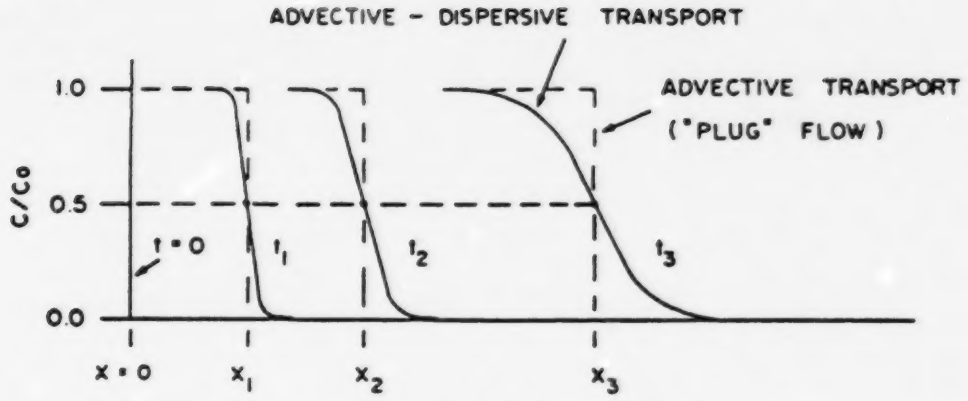

$$x_3 > x_2 > x_1 > x$$

$$t_3 > t_2 > t_1 > t$$

$$x_3/t_3 = x_2/t_2 = x_1/t_1 = \bar{v}$$

Figure 2.2 Breakthrough Concentrations in a One-Dimensional Solute Transport System Demonstrating the Deviation from Plug Flow caused by Dispersion (from Gillham and Cherry, 1982)

Gillham and Cherry (1982) provided a comprehensive review of the use and abuse of the advection-dispersion approach to dispersion studies in unconsolidated geologic media. In the basic Fickian approach to solute transport in geologic media, molecular diffusion effects are combined with mechanical dispersion to obtain a coefficient representing the total mixing process. This coefficient is known as the coefficient of hydrodynamic dispersion and is written as:

$$D_h = D_m + D$$

where D_h is the coefficient of hydrodynamic dispersion, D_m is the coefficient of molecular diffusion and D is the mechanical dispersion coefficient. D in its most general form is a second rank tensor comprised of longitudinal and transverse components. In a one dimensional flow system the longitudinal (D_L) and transverse (D_T) components are generally assumed to follow relations of the form:

$$D_L = \alpha_L V^n$$

and

$$D_T = \alpha_T V^n$$

where α is a characteristic length of the system known as its dispersivity, V is the interstitial groundwater velocity and n is an empirically derived quantity which is normally assumed equal to one.

Dispersion is often expressed in terms of a dimensionless parameter known as the Peclet Number (Pe) as:

$$Pe = \frac{VX}{D_h}$$

where X refers to a characteristic flow path length, typically the particle diameter. When n is set equal to one and molecular diffusion and transverse dispersion are assumed negligible, the Peclet number reduces to:

$$Pe = \frac{X}{\alpha_L}$$

It should be noted that the factors governing the dispersion of solute in hydrogeologic systems are still poorly understood. Part of this difficulty arises from the assumed Fickian behavior of the dispersion process. While some researchers (e.g., Gelhar et al., 1979; Güven et al., 1984) have concluded that this approach is valid at large distances or at large time, others (Matheron and Marsily, 1980; Neretnieks, 1979) have theoretically shown that in certain cases (e.g., where groundwater flow occurs parallel to stratifications or channels with a zero transverse dispersion component) dispersion tends to deviate from ideal Fickian behavior. Another major difficulty with the present formulation of dispersion is that it does not replicate observed behavior exactly. For example, due to its velocity dependence, models that are based on Fickian behavior may predict the dispersion of solute in an up-gradient direction. This effect has never been reported in laboratory observations or field experiments.

2.2 INFLUENCING FACTORS

As described above, mechanical dispersion is typically assumed to be a function of the interstitial groundwater velocity and a characteristic system parameter known as the dispersivity. Any processes that might alter the groundwater velocity would therefore affect the dispersion of solute in the system. These would include processes that affect the permeability, flow porosity or hydraulic gradient of the hydrogeologic system. Many of these parameters are affected by the same processes, sometimes in complicated and compensating ways. A change in temperature, for example, may have the following impact on the interstitial velocity of a hydrogeologic system:

1. Permeability modification - reduction due to thermal expansion of the rock mass; enhancement due to thermal cracking.

2. Porosity modification due to thermal expansion and/or thermal cracking.

3. Hydraulic gradient enhancement due to induced buoyancy.

Changes in stress may also affect rock properties (i.e., permeability and porosity) as well as fluid density which may alter hydraulic gradients. Dissolved solids concentrations may also impact fluid density resulting in modifications to hydraulic gradients.

Dispersivity is the other parameter required to quantify the mechanical dispersion process in a hydrogeologic system. Unfortunately dispersivity is not a parameter that can be measured directly but typically must be determined from data obtained from field tracer tests. As a result, dispersivity values are subject to considerable error since all of the errors associated with other parameters will be reflected in the dispersivity value. In spite of these difficulties it is generally believed that dispersivity is scale dependent. For porous media Pickens and Grisak (1981a) proposed a linear dispersivity function (for early time behavior) of the form:

$$\alpha_L = 0.1\ X$$

where X is the mean travel distance.

In addition, dispersivity is known to be heavily dependent upon system geometry (e.g., the nature of fracture networks) rendering the extrapolation of experimentally determined values to larger scale systems difficult. Furthermore, Raven (1986) interpreted the results of five field tracer tests in a single fracture and suggested that dispersivity in a single fracture was velocity dependent. He presented the dispersivity values obtained from analysis of five different tracer tests performed in a single fracture at different fluid velocities as evidence of this dependence (see Figure 2.3). The existence of such a relationship would tend to cast considerable uncertainty upon the applicability of induced gradient dispersivity values to natural systems.

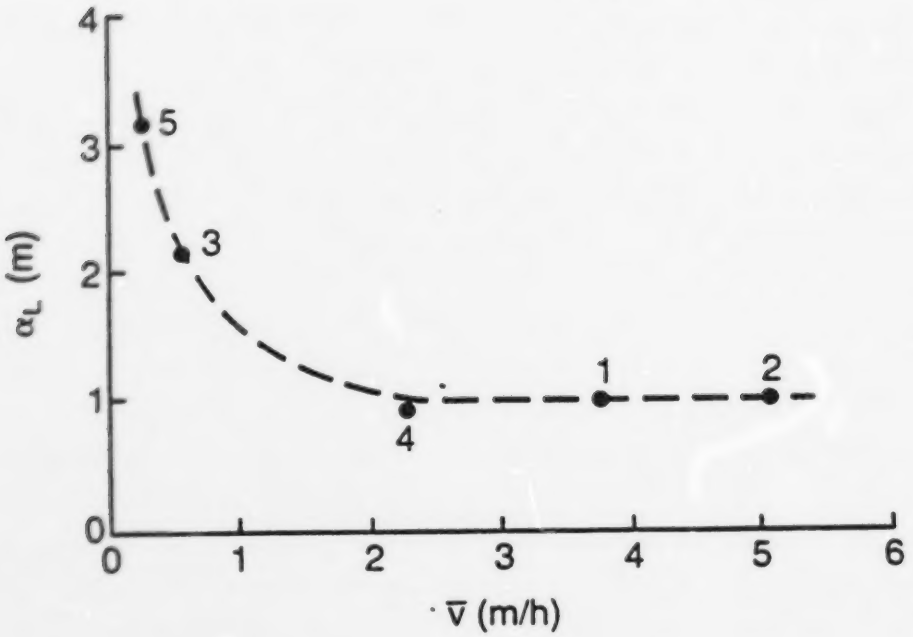

Figure 2.3 Variation of longitudinal dispersivity as a function of mean fluid velocity (from Raven, 1986)

2.3 SCALE CONSIDERATIONS

Dispersion results from the variations that exist in a natural groundwater system. These variations arise from a variety of mechanisms including viscous forces and drag (causing velocity variation within an individual fracture or pore) and heterogeneities. The existence of heterogeneous materials typically results in a spatial variation of permeability which in turn gives rise to velocity variations. The existence of these heterogeneities implies that dispersivity is likely to increase with mean travel distance. This is due to the fact that a wider range of heterogeneities is encountered with increasing travel distance. At some point, however, the sampling volume may be sufficiently large so that the effect of individual heterogeneities will diminish and the statistical properties of the sample may approach those of the population as a whole and dispersivity would approach a maximum value. This concept is analogous to the representative elementary volume concept discussed by Bear (1972) and depicted in Figure 2.4.

The conclusion that dispersivity may be scale dependent was reached independently by several researchers (e.g., Pickens and Grisak, 1981a; Schwartz, 1977; Fried, 1975) based on the comparison of the results of experiments conducted at different scales. A number of researchers have developed approaches to incorporate variable dispersivities (i.e., as a function of travel distance) into analytical techniques. This includes the approach utilized by Sauty et al. (1979) who varied dispersivity as a function of distance from an injection well. Gelhar et al. (1979) used a spectral representation technique to develop first-order solutions of a stochastic flow equation. The dispersivity value obtained from their analysis increased with travel distance approaching an asymptotic value dependent on the statistical properties of the medium. Recently, Güven et al. (1984) have theoretically shown that, in a stratified aquifer, the longitudinal

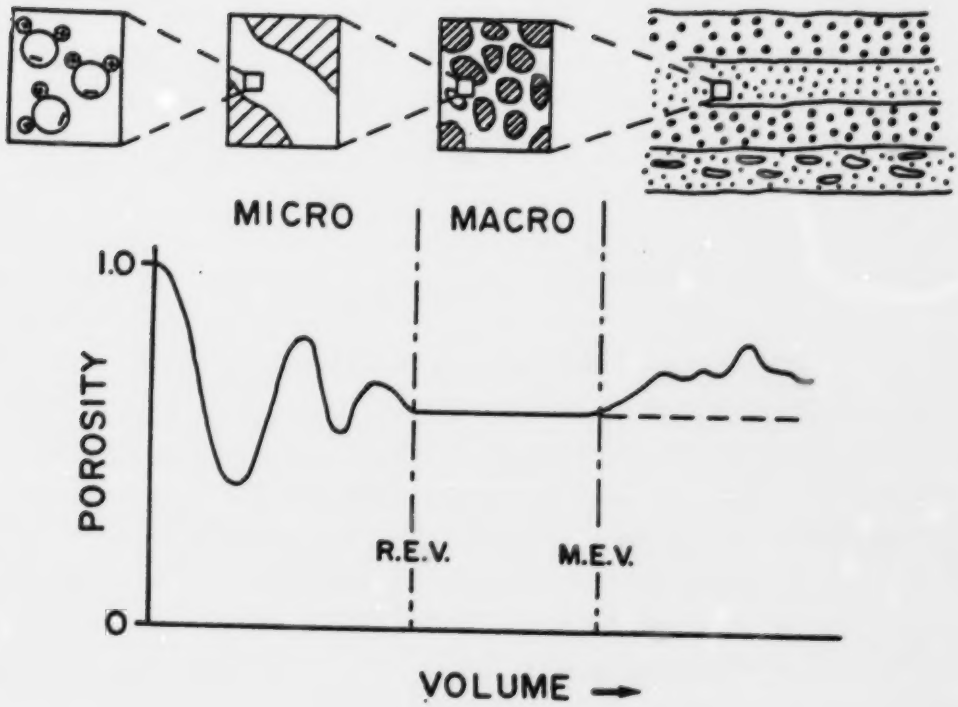

Figure 2.4 Variation of System Properties (porosity) with Sample Size (from Gillham and Cherry, 1982)

dispersivity increases with distance and approaches an asymptotic value. Pickens and Grisak (1981a) used a linear relationship of dispersivity versus travel distance to model transport in a stratified unconfined aquifer. Whether such a relationship would be applicable to a fractured crystalline rock system is unclear. Other suggested dispersivity function types (Pickens and Grisak, 1981b) have included parabolic, asymptotic and exponential. Lallemand-Barres and Peaudecerf (1978) presented a compilation of measured longitudinal dispersivity values as a function of the path length for various rock types (Figure 2.5). Their data supported the existence of a scale effect for dispersivity.

2.4 TEST METHODS

As discussed previously, the dispersivity of a hydrogeologic system is essential to the quantification of dispersion of solutes in hydrogeologic systems but is a parameter that cannot be measured directly. Typically, dispersivity estimates are obtained by analyzing the results of tracer experiments. Tracer tests may take a variety of forms, but typically fall into one of the following classifications:

- Natural Gradient Test
- Two Well (Injection-Withdrawal) Test
- Radial Convergent Test
- Radial Divergent Test

Natural gradient tests, as the name implies, involve injecting a tracer at one point in a hydrogeologic system, allowing it to move under its natural driving force, and then measuring the breakthrough concentration at some point down-gradient. This test offers the advantage of yielding a dispersivity representative of natural conditions. However, associated with this advantage are the

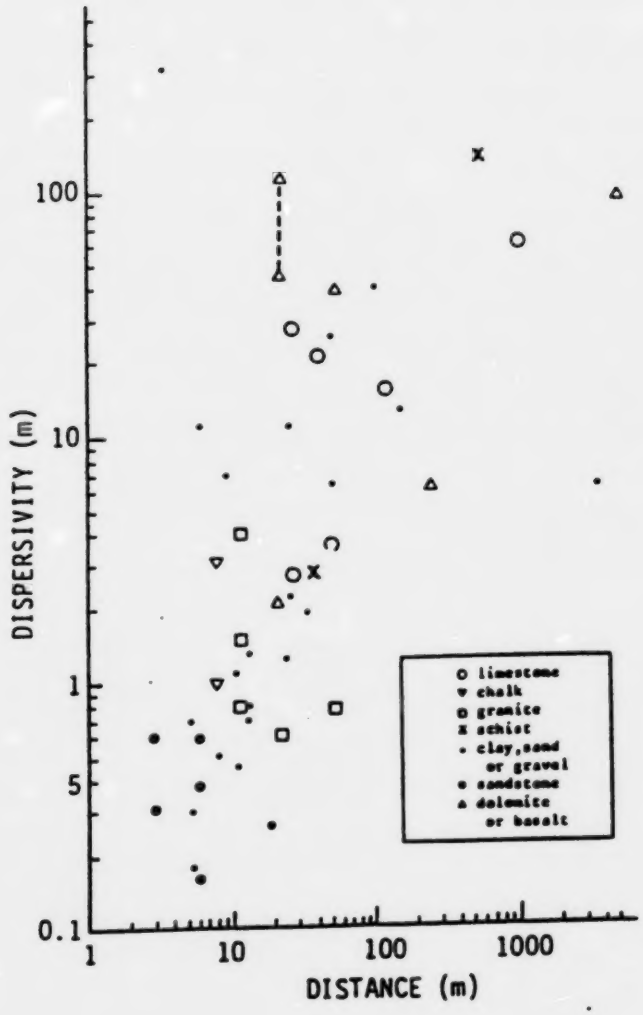

Figure 2.5 Dispersivity as a Function of Test Distance (from Lallemande-Barres and Peaudecerf, 1978)

disadvantages of long test times and/or small test distances due to the relatively small fluid velocities present in most natural hydrogeologic systems. Another major disadvantage of the natural gradient test is low probability of placing receiver wells in the correct location to sample the centre of mass of the tracer.

A two well (injection-withdrawal) tracer test offers the opposite advantages/disadvantages of a natural gradient test. Dispersivity values are obtained for systems having hydraulic gradients that may be orders of magnitude higher than those that exist naturally. However associated with these higher gradients are shorter test times. Two well tests require considerable field experience and advance planning in order to yield interpretable results. Some typical problems encountered with this type of test (in addition to the normal difficulties associated with all tracer tests) include:

- Provision of ample supply of uncontaminated injection water - requires estimate of test duration, injection rate and/or method of analysis capable of separating tracer concentration due to recirculation.

- Suitable well spacing - to enable sufficient recovery of tracer for analysis (will be a function of permeability, interconnected or flow porosity, flow rates).

Figure 2.6 presents a typical two-well recirculating test configuration (from Thompson, 1980).

Radial convergent tests involve monitoring a pumping well discharge for tracer injected (using a negligible flow rate) some distance from the pumping well. Convergent tests typically tend to be much more successful than divergent tests owing to a higher rate of tracer capture.

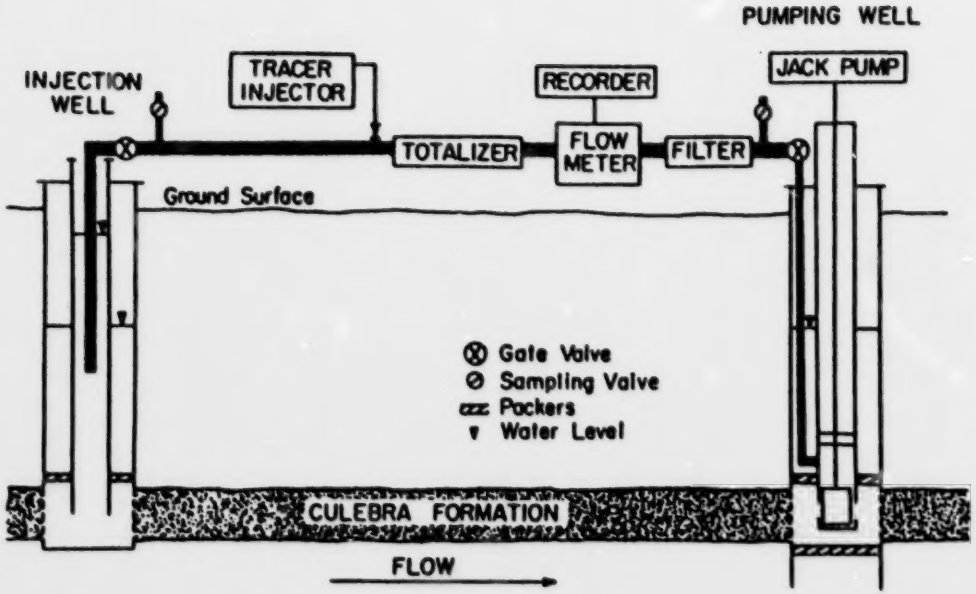

Figure 2.6 Typical Configuration of a Two-Well Recirculating Tracer Test (from Thompson, 1980)

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All tracer tests conducted for quantification of dispersion are subject to several common sources of error. These include:

- insufficient knowledge of the flow field and hydrogeologic system tested;
- artifical mixing - due to such things as dilution and mixing in boreholes and test instrumentation;
- imperfect tracer properties - e.g., surface adsorption is incorrectly accounted for;
- mechanisms ignored - matrix diffusion can alter the shape of the breakthrough curve and, if not considered in the analysis, may be interpreted as mechanical dispersion;
- background tracer concentrations may be non-zero;
- analytical or numerical solutions of the advective dispersive equation may introduce numerical dispersion/spatial truncation error which is identical to physical dispersion.

Steps can be taken, either in the test itself or the subsequent analysis to minimize or at least quantify these sources of error. For example, to counteract the adverse effects of wellbore dilution, the size of the test interval can be reduced (e.g., through the use of packers), downhole concentrations can be monitored (e.g., using a probe in the injection interval) or injection concentrations can be estimated through the use of mixing cell models.

Imperfect tracer properties can be accounted for by using two non-competing tracers or performing duplicate tests. Thompson (1980), Davis et al. (1980) and Davis et al. (1985) reviewed the commonly used tracers and comment on their appropriateness. As in the case of matrix diffusion, imperfect tracer effects such as adsorption can be removed by including such mechanisms in the analysis. Background levels of candidate tracers should be quantified and form one criterion in the selection of the tracer. Numerical dispersion present in numerical models may arise due to the selected space discretization. These problems can be avoided by ensuring that a sufficiently fine discretization is used. Lantz (1971) provided methods for quantifying this effect.

3. SITE SPECIFIC VALUES

In an earlier study conducted for AECB (GTC, 1986) the major sources of hydrogeologic data relevant to the deep disposal of radioactive waste in plutons were identified and described. It was found that the majority of the available well-documented data pertained to a relatively small number of sites. These studies could be classified as pertaining to:

1. Stripa Mine
2. Swedish Research Areas
3. Finnish Research Areas
4. Nevada Test Site (Climax granite)
5. Office of Crystalline Repository Development (OCRD) Room in Colorado School of Mines
6. Savannah River Plant
7. Oracle Site
8. Basalt Waste Isolation Program at Hanford
9. AECL's Underground Research Laboratory
10. AECL's Atikokan Research Area
11. AECL's Chalk River Research Area
12. AECL's Whiteshell Research Area
13. Miscellaneous Programs

As one might expect, studies aimed at characterizing dispersion in the groundwater at these sites form a subset of the above categories. That is, some of the sites have had little if any work performed for the purpose of evaluating dispersion. Dispersion studies that have been identified were conducted at the following sites:

1. Stripa Mine
2. Swedish Research Areas (Finnsjon and Studsvik)
3. Savannah River Plant
4. Oracle Site
5. Basalt Waste Isolation Program (at Hanford)

6. AECL's Chalk River Research Area
7. Miscellaneous Programs and Sites

The following sections discuss the investigations conducted at these sites for the purpose of characterizing dispersion. Detailed site descriptions have been presented in an earlier study (GTC, 1986) and have not been repeated herein. Table 3.1 summarizes the findings of the individual studies.

3.1 STRIPA MINE

In contrast to the extensive monitoring and analyses that have been conducted at the Stripa Mine for the purpose of characterising fracture networks, permeabilities and thermomechanical properties, little work has been conducted for the purpose of evaluating dispersion. One study of note is that reported by Abelin et al., (1985). In this study, a suite of sorbing and non-sorbing tracers were injected into single fractures at points 5 to 10 m above the roof of the 360 m level drift. A total of 5 injection and 31 sampling holes were drilled into the two fractures. Figure 3.1 presents a schematic view of the test hole locations. It was originally intended to use four classifications of tracers including:

- conservative (non-sorbing) tracers
- sorbing (analogs) tracers
- high molecular weight solutes
- particles of collodial size

A number of tracers were examined and the selected tracers are presented in Table 3.2. Note that no suitable colloidal sized particles were found. The tests were intended to be conducted under "natural" flow conditions. The "natural" flow conditions were actually radial convergent flow to an underground drift. The high hydraulic gradients (7.0 m/m) are considered unrepresentative of natural flow conditions in fractured granites.

Table 3.1 Summary of Tracer Tests in Crystalline Rocks for Dispersivity Determinations

Reference	Rock Type	α_L (m)	Distance[a] (m)	Depth (m)	Flow Field,[+] Tracer	Mass[x] Recovery (%)	Reliability	Comments
Neretnieks et al. (1982)	Granite (Stripa)	0.025	0.30	Core 360	Uniform, LS^-, ^3H	NR	Rel.	11 tests; disp. ranges 0.011 to 0.037 M (analyzed by channel model)
Moreno et al. (1985)	Granite (Stripa)	.0017-.0195	0.185	Core	Uniform, LS^-, ^3H, I^-,	NR	Rel.	
		.0034-.0264	0.270	NR	Br^-	NR	Rel.	
Abelin et al. (1985)	Granite (Stripa)	2.3	4.5	360	Rad. Conv., NaFl	NR	Unrel.	Sampling Point 2-6: Advection disp. analysis
		5.2	4.5	360	Rad. Conv., NaFl	NR	Unrel.	Sampling Point 2-8: Advection disp. analysis
		1.9	4.5	360	Rad. Conv., NaFl	NR	Rel.	Sampling Point 2-6: Advection disp. diff. analysis
		0.12	4.5	360	Rad. Conv., NaFl	NR	Rel.	Sampling Point 2-8: Advection disp. diff. analysis
		1.9	4.5	360	Rad. Conv., NaFl	NR	Rel.	Sampling Point 2.6: Advection disp. diff. = lab value
		3.9	4.5	360	Rad. Conv., NaFl	NR	Rel.	Sampling Point 2.8: Advection disp. diff. = lab value
Landstrom et al. (1978)	Granite (Studsvik)	7.8	51.0	70	Inj-With, ^{82}Br	NR	Rel.	57 hour test
		14.3	51.0	70	Inj-With, ^{85}Sr	NR	Unrel.	398 hour test
Landstrom et al. (1982) (1983)	Granite (Studsvik)	0.39	11.8	91	Inj-With, ^{131}I	NR	Rel.	
		0.47	11.8	91	Inj-With, ^{131}I	NR	Rel.	
		0.59	11.8	91	Inj-With, ^{131}I	NR	Rel.	
Gustafsson & Klockars (1981)	Gneissic Granite (Finnsjon)	1.5	30.0	100	Inj-With, I^-	67	Rel.	Instantaneous Tracer Inj; 30 and 62 hour tests
		0.9	30.0	100	Inj-With, I^-	67	Rel.	Instantaneous Tracer Inj; 25 and 91 hour tests
		0.9	30.0	100	Inj-With, I^-	67	Rel.	Continuous 38.5 hour test
		1.2	30.0	100	Inj-With, Cr EDTA	67	Rel.	Continuous 37 hour test
Cullen et al. (1985)	Quartz Monzonite (Oracle)	0.334	9.1	75	Rad. Conv. SCN^- + others	NR	Uncert.	
		2.25	6.05	73	Rad. Conv. Fluorocarbons	NR	Uncert.	
		2.23	6.05	73	Rad. Conv. Fluorocarbons	NR	Uncert.	
		2.15	6.05	81	Rad. Conv. I^-, Br^-	NR	Uncert.	

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Table 3.1 Summary of Tracer Tests in Crystalline Rocks for Dispersivity Determinations (cont'd)

Reference	Rock Type	α_L (m)	Distance* (m)	Depth (m)	Flow Field,+ Tracer	Mass× Recovery (%)	Reliability	Comments
Webster et al. (1970)	Chlorite-hornblende Schist & hornblende gneiss (Savannah River)	134.0	538.0	305	Inj-With, ^{3}H	33	Unrel.	2 year test period
Leonhart et al. (1985)	Basalt (Hanford)	0.84	16.8	1200	Inj-With, SCN^-	60	Unrel.	
Gelhar (1982)	Basalt (Hanford)	0.60 (0.46)	17.07	1200	Inj-With, ^{131}I	NR	Unrel.	Analysis by two point method (Numerical Analysis)
Davison (1982)	Granite (CRNL)	0.1	12.0	103	Inj-With, I^-	NR	Unrel.	Analyzed Using Grove & Beetem (1971)
Raven and Novakowski (1984)	Monzonitic Gneiss (CRNL)	0.5	37.9	35	Inj-With, ^{82}Br RdWt	10	Unrel.	15 hour test
		1.0	12.7	30	Inj-With, RdWt	10	Unrel.	13.5 hour test
Novakowski et al. (1985)	Quartz Monzonite Gneiss (CRNL)	1.4	10.56	100	Inj-With, ^{82}Br	60-80	Rel.	30 hour test
Raven (1986)	Granite (CRNL)	1.0	12.7	34	Inj-With, ^{82}Br	50-60	Rel.	
		1.0	12.7	34	Inj-With, NaFL	50-60	Rel.	
		2.1	12.7	34	Rad. Conv. ^{82}Br	50-60	Rel.	
		0.9	12.7	34	Inj-With, ^{82}Br	50-60	Rel.	
		4.0	29.8	35	Inj-With, ^{82}Br	50-60	Rel.	
Raven and Novakowski (1986)	Granite (CRNL)	2.0	37.9	35	Inj-With Br	80	Unrel.	33 hour test
Tester et al. (1982)	Granite (Fenton Hill)	59.1	100.0	3000	Inj-With, NaFl	NR	Unrel.	One-dimensional analysis
		94.2	100.0	3000	Inj-With, NaFl	NR	Unrel.	Dispersivity from Pe
		94.4	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		112.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		35.8	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		30.6	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		34.7	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		19.5	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		36.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		28.1	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		31.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		76.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	" "
		25.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	Two-dimensional analysis with matrix diffusion
		50.0	100.0	3000	Inj-With, NaFl	NR	Unrel.	Two-dimensional analysis without matrix diffusion

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Table 3.1 Summary of Tracer Tests in Crystalline Rocks for Dispersivity Determinations (cont'd)

Reference	Rock Type	α_L (m)	Distance* (m)	Depth (m)	Flow Field,+ Tracer	Mass× Recovery (%)	Reliability	Comments
Robinson and Tester (1984)	Granite (Fenton Hill)	15-60	300.0	3000	Inj-With, ^{82}Br	65-90	Rel.	One-dimensional analysis accounting for recirculation
		5.4	300.0	3000	Inj-With, ^{82}Br	65-90	Rel.	Two-dimensional analysis accounting for recirculation
Goblet et al. (1980)	Granite (Massif)	1.0	12.0	40	Inj-With, (four tracers)	30-75	Rel.	Analysis by type curve (Sauty, 1977)
Calmels et al. (1979)	Granite (Massif)	1.5	11.85	40	Inj-With, Cl^-	75	Rel.	" "
		0.8	11.85	40	Inj-With, I^-	72	Rel.	" "
		0.6	11.85	40	Inj-With RdWt	38	Rel.	" "
		4.0	11.35	40	Inj-With, NO_3^-	73	Rel.	" "
		0.6	11.65	40	Inj-With, RdWt	31	Rel.	" "
		0.6	11.85	40	Inj-With, Sr^{++}	31	Rel.	" "
		0.6	11.85	40	Inj-With, Cs^+	29	Rel.	" "
Calmels et al. (1979)	Granite (Massif)	0.0008	0.04	Core 1	Uniform, NO_3^-	NR	Rel.	Analysis by type curve (Sauty, 1977)
		0.0025	0.04	Core 1	Uniform, RdWt	NR	Rel.	
		0.0050	0.04	Core 1	Uniform, NaFl	NR	Rel.	" "
		0.0004 & 0.0011	0.04	Core 2	Uniform, I^-	NR	Rel.	" "
		0.0007 & 0.0011	0.04	Core 2	Uniform, Cl^-	NR	Rel.	" "
		0.0007 & 0.0040	0.04	Core 2	Uniform, Sr^{++}	NR	Rel.	" "
		0.0011 & 0.0022	0.04	Core 2	Uniform, Cs^+	NR	Rel.	" "

*Between Injection and Withdrawal Points
+LS = Lignosulphate
NaFl = Sodium Fluorescein
RdWt = Rhodamine WT
SCN = Thiocyanate
×NR = Not Reported

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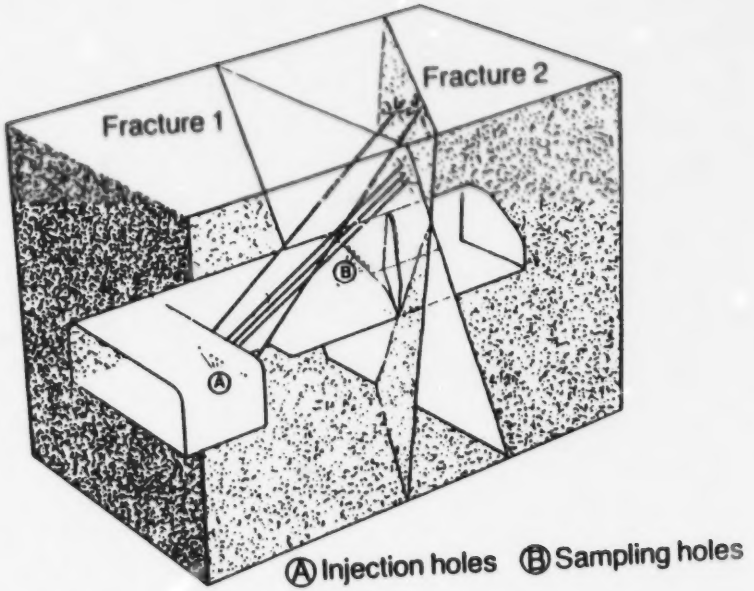

Figure 3.1 Test Hole Locations for In Situ Tracer Test Conducted at Stripa Mine (from Abelin et al., 1985)

Table 3.2 Tracers used as Part of the Single Fracture Experiment at Stripa (Abelin et al., 1985)

			Injection concentration ppm
Nonsorbing:	Albumin	(large molecule)	100
	Brom Thymol Blue	(BTB)	150
	Elbenyl	(dye)	40
	Eosin	(dye)	18, 93
	Iodide	(anion)	80
	Uranine	(dye)	23, 31
Sorbing:	Cs I	(Oxidation state)	60
	Sr II		30
	Eu III		0.02
	Nd III		0.2
	Th IV		< 0.001
	U IV and VI		3

Unfortunately, the experiment was plagued by a number of problems which reduced the overall success of the test. For example tracer injections were achieved by using a small overpressure (e.g., 10%) above the natural pressure. Unfortunately the use of such small injection pressures may cause considerable uncertainty in flow rates since small variations in pressure may result in large variations in flow. Other problems encountered included the absence of any sorbing tracer at the collection points and the lack of data for Cr-EDTA (due to equipment malfunction) and Albumin (due to low concentrations).

Those results that could be analyzed were modeled using the following approach.

- determination of fracture properties using the results of the conservative tracer runs;
- prediction and analysis of sorptive transport properties.

The models employed in the analyses of the tracer experiments are based on those used by Moreno et al. (1983) in the analyses of tracer tests conducted at Finnsjon. Basically the models used in the analysis of the Stripa data consist of:

1. advection dispersion model;
2. advection dispersion diffusion model;
3. channelling model.

The first model assumes transport along a single fracture and considers advection and dispersion along the fracture and sorption (via an equilibrium sorption isotherm) onto the walls of the fracture. Abelin et al. (1985) use an analytical solution to the transport equation developed by Lapidus and Amundsen (1952) to fit the Uranine (Na-Fluorescein) tracer injected at borehole H2 and observed at sampling holes 2-6 and 2-8 located approximately 4.5 m away. Best fit dispersivity values were 2.3 m and 5.2 m for locations 2-6 and 2-8, respectively.

The data at these two sampling locations were also fit using a model which considers diffusion of solute into the rock matrix in addition to the mechanisms outlined above. Two sets of model runs were made. In one set four parameters were adjusted to obtain the best possible fit with the observed data. These included the Peclet Number, mean residence time, dilution factor and a diffusion based parameter. Using this approach, dispersivities of 1.9 and 0.12 m were fit to the breakthrough concentrations measured at sampling points 2-6 and 2-8. These data were subsequently fit using a set value for the diffusion parameter based on laboratory measurements. This approach yielded dispersivity values of 1.9 m and 3.9 m respectively.

The third model used to fit the breakthrough concentrations was a channelling model originally proposed by Neretnieks (1983). This model considers only advection along the channels and diffusion into the rock matrix. Like the advection diffusion dispersion model, the channel model requires four parameters to be fit as part of a calibration. These include a diffusion parameter, dilution factor, mean residence time and the variance of channel widths (assumed to be lognormally distributed). Dispersion, as such, is not explicitly included in the channel model but is inherent in the channel width distribution. Abelin et al. (1985) report standard deviations for this distribution of 0.38 and 0.17 (for sampling points 2-6 and 2-8) by letting all four parameters vary. Values of 0.38 and 0.47 were obtained by fixing the diffusion parameter to a predetermined laboratory value. Figure 3.2 presents the fitted model concentration curves together with the observed data points for all three models.

A second study aimed at obtaining solute transport parameters in the Stripa granite is reported by Neretnieks et al. (1982). In this study, the migration of a series of sorbing (cesium and strontium) and non-sorbing (tritiated water and lignosulphate molecules) tracers in a 30 cm long (20 cm diameter) granite core was studied. The core contained a natural fissure oriented parallel to the direction of the

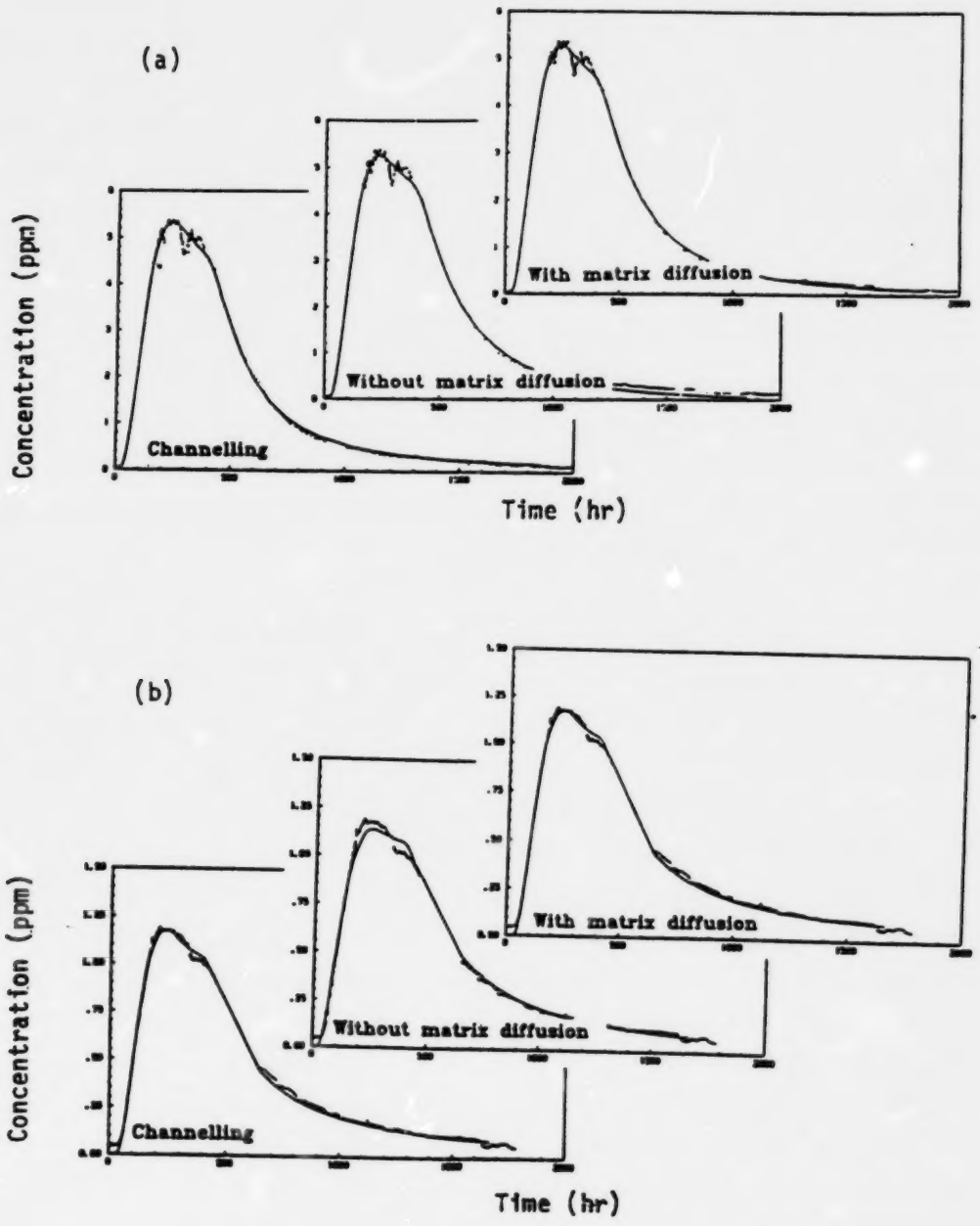

Figure 3.2 Comparison between Calculated (line) and Observed (points) Concentrations (ppm)
(a) at Sampling Point 2-6
(b) at Sampling Point 2-8
(from Abelin et al., 1985)

core. A total of eleven non-sorbing tracer experiments (six using tritiated water, five using lignosulphonate) were conducted at various constant flow rates ranging from 0.175 to 0.0258 ml/min (2.92×10^{-9} to 4.30×10^{-10} m^3s^{-1}). These experiments were anlayzed using a channelling model which included the effect of surface sorption, matrix diffusion and matrix sorption. These runs were used to establish the fracture hydraulic parameters (e.g., channel dispersion) of the experimental setup. Dispersivities may be back-calculated from information contained in Neretnieks et al. (1982) and can be seen to range from 11.1 to 38.0 mm over the 300 mm core length. Neretnieks et al. (1982) reported an average value of 25 mm. This average value is incorporated into the sorbing tracer model fits (in the form of a channel width standard deviation) and is not calculated explicitly for these runs.

A second set of laboratory tracer experiments performed on granite cores from the Stripa mine was reported by Moreno et al. (1985). These tests were conducted on two 10 cm diameter cores with lengths of 18.5 cm and 27.0 cm. Each core contained a single fracture oriented parallel to the axis of core. A number of tracer experiments were conducted using a range of flow rates (0.22 to 1.62 ml/min; 3.67×10^{-9} to 2.7×10^{-8} m^3s^{-1}) and a number of sorbing (e.g., strontium) and non-sorbing tracers (sodium lignosulphate, tritiated water, iodide and bromide). Tests consisted of monitoring the breakthrough of tracer resulting from a step input of tracer and typically lasted between 10 and 100 min. Moreno et al. (1985) used two models to analyze the resulting data: a hydrodynami dispersion-diffusion model of a single fracture and a channeling dispersion-diffusion model. The approach followed by Moreno et al. (1985) involved estimating a Peclet number and the water residence time by fitting the data of the non-sorbing tracers (while using a constant diffusion coefficient of 10^{-13} m^2/s). The average Peclet number determined by this set of runs was input into the sorbing tracer runs and both tracer residence times and sorption parameters were obtained by fitting the data.

Peclet numbers, as determined by the hydrodynamic dispersion diffusion model, were found to range from 9.5 to 109 for the non-sorbing tracers used on Core A. This corresponds to a dispersivity range of 0.17 cm to 1.95 cm. Moreno et al. (1985) indicated a Peclet number of 20 (dispersivity of 0.93 cm) could be considered as representative. Tests conducted on Core B yielded Peclet numbers ranging from 9.5 to 80.2 (dispersivity ranging from 0.34 cm to 2.84 cm) with an average value of 15 (1.8 cm).

Moreno et al. (1985) presented the results of the channeling dispersion model in the form of standard deviations of the lognormal distribution of channel widths. These values ranged from 0.096 to 0.220 for tests conducted on Core A, the only core analyzed using this model. From these results, it may appear that the channeling dispersion model is capable of fitting the data better since the range on the fitted parameter is smaller. However, if one examines the theoretical relationship between the Peclet number and the standard deviation of channel widths (σ) as proposed by (Neretnieks, 1983):

$$\frac{2}{Pe} = \exp(4\sigma^2) - 1$$

the reason for the relatively small range of standard deviations may be apparent. In fact, Moreno et al. (1985) concluded that both models were capable of fitting the observed data equally well. Moreno et al. (1985) also indicated the contribution of molecular diffusion to the overall transport process was relatively minor and attributed this to both the relatively low value of the diffusion coefficient together with the short duration of the test.

3.2 SWEDISH SITES

In addition to the tests conducted at Stripa, tracer tests (for the purpose of evaluating dispersivity) have been conducted at two other research areas - Studsvik and Finnsjon. A number of tracer tests have been conducted at Studsvik as reported by Landstrom et al. (1982). The first of these tests were conducted in 1977 and are described in detail in Landstrom et al. (1978). Briefly, this set of tests consisted of pumping a single well at 6 $L \cdot min^{-1}$ (1×10^{-4} $m^3 s^{-1}$) from a fracture zone at a depth of approximately 72 m. Radionuclides such as selenium, technetium, tin, cesium, iodine, neodyminn, strontium and bromide were injected in three separate pulses over the period from 9 February to 22 March 1977. The breakthrough concentrations were analyzed using an analytical solution to the solute transport equation for the case of an instantaneous injection (after Lenda and Zuber, 1970). A dispersivity of 7.8 m was calculated using the breakthrough curve corresponding to bromide while a value of 14.1 m was calculated using the curve corresponding to strontium. Both values were calculated for the same flow path (of 51 m) and no reason for the discrepancy was suggested. It is conceivable however that the difference may be attributable to the fact that strontium is much more strongly adsorbed than bromide and errors in incorporating this effect may be responsible for some difference. In addition, strontium will be subjected to diffusional effects over a longer period of time and may be subjected to more losses than the relatively inert bromide. The second set of tracer experiments were conducted in 1980-1981 at a different part of the site. A number of in situ tracer migration studies were conducted at this time using both non-sorbing (e.g., ^{131}I and ^{3}H) and sorbing tracers (strontium). Landstrom et al. (1982) described the ^{131}I test

in which a fracture zone at a depth of 91 to 92.3 m was pumped at a rate of 1.2 $L \cdot min^{-1}$ (2×10^{-5} $m^3 s^{-1}$) while tracer was injected in a well located 11.8 m away. The observed breakthrough concentration was analyzed by fitting the breakthrough curves in accordance with the procedure proposed by Lenda and Zuber (1970). This method indicated the existence of three partial curves, which were interpreted as representative of different flow paths. A dispersivity was obtained for each of these flow paths with values ranging from 0.39 m to 0.59 m (Landstrom et al., 1983).

Finnsjon has been the site of five tracer tests (Gustafsson and Klockars, 1981). These tests were all radial convergent tracer tests conducted in the same intervals of the same boreholes. The tests differed mainly in the nature of the tracer injection (e.g., instantaneous or continuous) or combinations of tracers used. Table 3.3 summarizes the tracer tests conducted at Finnsjon. All of these tests consisted of pumping the interval 100-102 m in borehole G1 at a fairly constant rate while injecting tracer over the 91-92 m interval of borehole G2, located 30 m away.

The results of one of these tests was selected as a test case for an international code comparison (INTRACOIN). As such this particular set of field data (which involved the continuous injection of iodide and strontium over 350 hours) has been analyzed by several groups of researchers (Hodgkinson and Lever, 1982; Moreno et al., 1983; Gustafsson and Klockars, 1981). Gustafsson and Klockars (1981) are the only researchers who have analyzed more than one of the tests conducted at Finnsjon. The instantaneous tracer injection tests were analyzed using a solution proposed by Lenda and Zuber (1970) while the continuous tracer injection tests were analyzed using a solution of

Table 3.3 Tracer Tests Conducted at Finnsjon (Gustafsson and Klockars, 1981)

Test	Tracer	Injection technique	Injection concentration C_o
1	Rd WT	Instantaneous	166 ppm
	NO_3^-		2 M
2	Rd WT	Instantaneous	166 ppm
	I^-		1 M
3	Br^-	Instantaneous	2 M
	NO_3^-		2 M
4	Cr-EDTA	Continuous	200 ppm
	I^-		$6.7 \cdot 10^{-2}$ M
5	Sr^{2+}	Continuous	$9.4 \cdot 10^{-2}$ M
	I^-		$6.7 \cdot 10^{-2}$ M

Ogata and Banks (1961). Neither solution accounts for matrix diffusion and so are only appropriate for relatively short time intervals when such effects are not significant. By analyzing the observed breakthrough concentrations, Gustafsson and Klockars interpreted the tests to suggest the existence of two pathways. The dispersivity of both these pathways varied slightly from test to test depending on the tracer used and the nature of the test. In all cases the dispersivity calculated from these tests fell within the range of 0.9 to 1.2 m. The observed and calculated breakthrough concentrations for two of these tests are presented in Figure 3.3. It is worth noting that the models utilized by Gustafsson and Klockars were incapable of replicating the reduced solute concentrations observed in the pumping well. The calculated concentrations have been scaled linearly downwards to match the approximate magnitude of the observed values. Gustafsson and Klockars acknowledge this fact and suggest that reactions between the tracer and rock or matrix diffusion may account for such observations.

Hodgkinson and Lever (1982) analyzed the data using a model of tracer movement through a single fracture. Their model is relatively sophisticated compared to other models used to analyze similar tests and, in addition to including the effects of radial advection and dispersion, it also considers kinetic surface sorption and diffusion into the rock matrix with equilibrium bulk sorption. The model of Hodgkinson and Lever (1982) is also somewhat unique in their treatment of dispersion. They assume that the dispersion coefficient is proportional to the square of the groundwater velocity as described earlier (Section 2.1). As a result the dispersivity parameter obtained from their analysis has the units of time and was found to be, for both strontium and iodine, 370 s. It is interesting to note the relative importance of the various mechanisms considered by this analysis

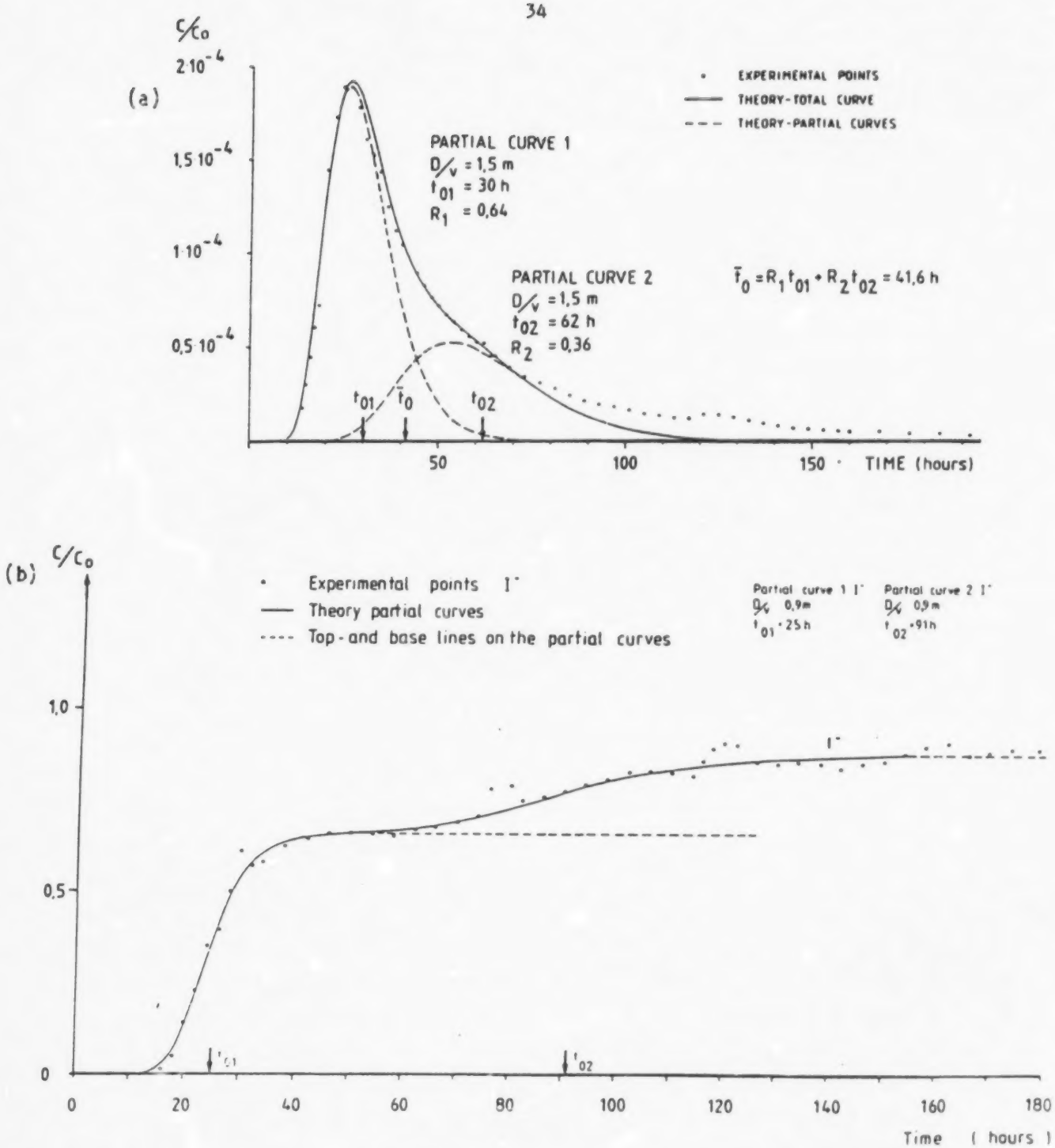

Figure 3.3 Calculated and Observed Breakthrough Concentrations for Tracer Tests Conducted at Finnsjon
(a) I^- Test 2
(b) I^- Test 5
(from Gustafsson and Klockars, 1981)

technique. For example kinetic sorption was found to be important in terms of explaining the relatively low capture of strontium at the production well. Longitudinal dispersion was found to be relatively unimportant and, as Hodgkinson and Lever pointed out, an acceptable match could be obtained with no longitudinal dispersion.

Moreno et al. (1983) also analyzed the strontium and iodine tests using a number of models to account for a variety of mechanisms. More specifically they use four models classified as:

1. hydrodynamic dispersion in several pathways;
2. hydrodynamic dispersion - diffusion;
3. channeling dispersion - diffusion;
4. hydrodynamic dispersion - diffusion with stagnant water.

The first of these models (i.e., hydrodynamic dispersion in several pathways) assumes that solute transport occurs through separate parallel fissures. The model considers advection and hydrodynamic dispersion along the fissure and adsorption (via an equilibrium adsorption isotherm) onto the walls of the surface. The iodine tracer test was analyzed for the purpose of calculating the hydraulic properties of the fissures. A number of analyses were conducted in which the number of pathways (i.e., fracture planes) was varied. It was found that three pathways could adequately reproduce the observed behavior if a loss factor (of 0.4) was assumed to account for the low recovery of strontium. The dispersivity for this best fit case was 0.95 m.

The second model employed by Moreno et al. (1983) was the hydrodynamic dispersion diffusion model. This model assumed that flow occurs through a single fracture and considers, in addition to the processes described for the previous model, molecular diffusion into the rock matrix as well as adsorption within the matrix. Unfortunately

the best fit that could be obtained using this model resulted in a diffusion related parameter being almost three orders of magnitude larger than that based on laboratory observations.

The third model constructed by Moreno et al. (1983) assumed that solute transport occurs through a fracture which is comprised of a number of parallel channels. Fissure widths are assumed to correspond to a lognormal distribution while longitudinal dispersion in an individual channel is assumed to be negligible. Hence the only dispersion that is assumed to exist is that due to the difference in channel properties. The model also includes the effect of adsorption onto the walls of the channel, diffusion into and adsorption within the rock matrix. Again all adsorption is assumed to correspond to an equilibrium isotherm. As with the previous model, difficulties arose when comparing matrix diffusion parameters resulting from model calibration and those obtained from laboratory experiments. The value obtained from fitting to the field test data was approximately two orders of magnitude less than that determined in the laboratory.

The final model employed by Moreno et al. (1983) is very similar to the channeling dispersion and diffusion model described above. In addition to the mechanisms described therein, the final model also considered longitudinal hydrodynamic dispersion and molecular diffusion into stagnant fluid zones that separate the channels through which fluid flows. The best fit between calculated and observed data occurred at a Pe number of 10 for the non-sorbing (iodide) tracer. The best fit obtained for strontium utilized a molecular diffusion coefficient that was one order of magnitude less than that obtained through laboratory experiments.

3.3 SAVANNAH RIVER

While in situ tracer experiments have been conducted on a number of occasions at the Savannah River Plant (Marine, 1979; Marine, 1980) only one of these studies (Webster et al., 1970) has been used to assess the dispersive nature of groundwater flow in fractured crystalline rocks. This study, conducted in 1970, represents one of the earliest tracer tests successfully carried out in a fractured rock environment. The test consisted of injecting a pulse of tritium (300 curies) in a fracture zone located in a borehole (DRB 5) between a depth of approximately 244 to 366 m (800 to 1200 ft). The pumping well, DRB 6, located some 538 m (1765 ft) away, was pumped at an average rate of 7.9 gpm (5×10^{-4} $m^3 s^{-1}$) over the two year test duration. With the exception of several equipment failures, injection and withdrawal rates were the same.

Webster et al. (1970) developed an analytical solution to the steady state flow field that exists around a two well (injection withdrawal) system. They subsequently used this flow solution together with the one dimensional diffusion-dispersion transport solution of Brenner (1962) to analyze the breakthrough concentration of tritium at the withdrawal well. Using this approach Webster et al. (1970) obtained a dispersivity value on the order of 134 m for the results of their tracer test.

3.4 ORACLE SITE

The first (and so far only reported) attempts to characterize the in situ dispersivity at the Oracle site in south eastern Arizona are those reported by Cullen et al. (1985). These tests have included both two dimensional anisotropic convergent tests as well as three dimensional anisotropic divergent tests. While the convergent tests have produced meaningful results, the divergent tests have yet to be successful.

A total of four separate tracer tests were conducted at the site. The first of these was conducted on 3 April 1981 and consisted of pumping one well (H 2) from a 75 m depth at a constant rate of 9.5 $L \cdot min^{-1}$ (1.58×10^{-4} $m^3 s^{-1}$) while injecting a variety of organic and inorganic tracers (e.g., thiocyanate, acetate, KHP, benzote) in three surrounding boreholes. Only a single dispersivity value (of 33.4 cm) was reported corresponding to an injection well located approximately 9.1 m away. The second tracer test consisted of pumping the same well while injecting tracers in two surrounding boreholes. Sodium benzote was injected in one well while a combination of tracers (fluorosalicylic acid and trifluoro-metabenzoic acid) was injected in the other well. Difficulties with the analysis of this test arose due to the inability to maintain a constant pumping rate throughout the test.

In spite of these difficulties, a dispersivity value of 2.25 m for one well located 6 m away was reported. The third tracer test employed the same test configuration as the second test, only a much lower (and presumably constant) pumping rate was employed. A dispersivity value of 2.23 m was calculated for the same test length as the second test. The fourth and last test reported by Cullen et al. (1985) consisted of pumping the same well as in all previous tests and injecting iodide and bromide into two surrounding wells. A dispersivity of 2.15 m was calculated for the same test length reported earlier.

The dispersivity values reported by Cullen et al. (1985) are open to some interpretation as the tracer injection methods used at the Oracle site do not likely approximate the slug injection assumption used in their analytical model.

3.5 BASALT WASTE ISOLATION PROGRAM - HANFORD

Two tracer tests were reported to have been conducted in the basalt flows under the Hanford Reservation in Washington (Leonhart et al., 1985). Both of these tests were conducted in the same location using the same test technique (i.e., two-well recirculating test). The

first of these tests was conducted in December, 1979 and it differed from the second in its choice of tracers, detection methods and flow rates. The earlier test used a solution containing ^{131}I which was injected at well DC-8 and detected in well DC-7 by means of a gamma radiation counter located at the wellhead. Flow rates during this test varied between 7.5 and 13 $L \cdot min^{-1}$ (1.25×10^{-4} and 2.17×10^{-4} $m^3 s^{-1}$) with only about two-thirds of the water removed being reinjected. Both the tests were conducted using the same test intervals, 20.5 m in length in DC-7 and 22.4 m in length in DC-8, located at a depth of approximately 1200 m. Borehole gyroscopic surveys indicate that the distance between these boreholes varies from 16.7 to 16.9 m. The second test was conducted in January 1982 using potassium thiocyanate (KSCN) as a tracer. Again the tracer was injected in well DC-8 and detected in DC-7 this time using an ultraviolet detector. Injection and withdrawal rates were maintained at a constant rate of 3.8 $L \cdot min^{-1}$ (6.33×10^{-5} $m^3 s^{-1}$) for two days prior to the start of tracer injection as well as the forty hour period over which the test was conducted.

Both tests were analyzed using a curve matching technique developed by Gelhar (1982) based on the theoretical derivation presented in Gelhar and Collins (1971). This approach was developed in order to analyze pulse tracer tests. Up to this point the majority of tracer tests utilized a step injection configuration and were typically analyzed using the approaches of Webster et al. (1970) or Grove and Beetem (1971). The concentration breakthrough curve of a pulse injection test has the advantage of being more sensitive to changes in dispersivity than a step input test. The Gelhar (1982) analysis method incorporates some simplifying assumptions to enable the derivation of a solution. In addition to the standard assumptions regarding homogeneity and isotropy, the method further assumes that transverse dispersion is negligible and that the flow field is steady. Gelhar (1982) indicates that the assumption regarding transverse dispersion should be valid for those tests where the longitudinal dispersivity is less than one tenth of the interwell distance. Tests that violate this criteria may be complicated by other factors such as displacement dependent dispersivity and non-Fickian behavior (Gelhar et al., 1979).

The resulting dispersivity estimates for these tests are 0.60 m and 0.84 m for the December 1979 and January 1982 tests respectively. An alternate method of analysis developed by Science Applications Inc. (as reported in Gelhar, 1982) based on Gelhar's (1982) approach yielded a value of 0.46 m for the first test. These values are all relatively close considering the typical precision and accuracies present in most field tests. The results however, may be influenced by dispersion resulting from flow in the injection and withdrawal tubing. Residence times of tracer in the tubing approximates the average residence time of tracer in the formation and therefore the calculated dispersivities may be overestimated.

3.6 CHALK RIVER NUCLEAR LABORATORIES

The Chalk River Nuclear Laboratories (CRNL) Research Area has been the site of numerous tracer tests conducted in the past ten years (Davison, 1981; Davison, 1982; Raven and Novakowski, 1984; Novakowski et al., 1985a,b; Raven, 1986). The earliest of these tests was conducted in 1979 (as described by Davison, 1981) and involved injecting a slug of Cl^- (225 ppm) over a forty-five minute period into interval 102 to 105.5 m of borehole CR-6. The pumping zone was located 10 m away over interval 98 to 108 m of borehole CR-7. The test was a recirculation test and hence the injection and withdrawal rates were equal averaging 5×10^{-6} m^3s^{-1} over the entire test period of 13 hours. Unfortunately either this test duration proved to be too short or downhole dilution too great as chloride concentrations measured in the production well never exceeded background ($\approx$5 ppm) levels. A second test conducted in the same boreholes (and test intervals) in the summer of 1980 proved to be more successful. In this test the injection/withdrawal rate averaged 3.3×10^{-5} m^3s^{-1} with a tracer solution of iodine being injected over the entire test period of 24 hours. Davison (1982) described this test and the subsequent analysis in detail. The analysis was conducted using the GROVE model (Grove and Beetem, 1971) which basically consists of

coupling a number of one dimensional solutions to the solute transport equation. The solutions are applied to the streamlines representing the steady-state flow field that exists in a two well (injection-withdrawal system). By using this approach and attempting to consider a mixing function in the borehole equipment, a dispersivity of 0.1 m was fit to the data.

Another series of tracer tests was conducted at CRNL in 1983, as reported by Raven and Novakowski (1984, 1986). This series of tests consisted of two tests, one conducted in boreholes FS-8 and FS-9, the other in boreholes FS-6 and FS-15. The first of these tests (i.e., FS-8 and FS-9) involved the pulse injection of both ^{82}Br and a fluorescent dye (Rhodamine Wt) at 30 to 35 m depths. Injection and production rates of the two wells (located 37.9 m apart) were constant at 3.6×10^{-5} m^3s^{-1}. The results (i.e., breakthrough concentration) of this test were analyzed using the GROVE Model (modified from Grove and Beetem, 1971). The major difference between the field test conditions and the assumptions inherent in the analytical procedure is the presence of recirculated tracer in the injection water under field conditions. The presence of the recirculated tracer makes the analysis of late time data difficult. Raven and Novakowski (1984) were able to fit the early time portion of the breakthrough curve using a longitudinal dispersivity of 0.5 m. The second test, conducted in 1983, was also a recirculation test, this time conducted over the 30 to 35 m interval of boreholes FS-6 and FS-15. Rhodamine Wt tracer was injected as a pulse input into well FS-6 and monitored 12.7 m away in the production water from FS-15. The flow rate over the test period (13.5 hours) averaged 1×10^{-5} m^3s^{-1}. Using the GROVE model Raven and Novakowski (1984) were able to fit the leading edge of the breakthrough concentration curve by using a dispersivity of 1.0 m. Again the inability of the GROVE model to replicate tracer recirculation precluded matching later portions of the curve. Raven and Novakowski (1986) subsequently retested and reanalyzed the ^{82}Br tracer test in boreholes FS-8 and FS-9 considering the recirculation effects and transit times in the borehole instrumentation and obtained a dispersivity of 2.0 m.

Novakowski et al. (1985) presented the results of two well injection withdrawal tracer experiments conducted and analyzed in 1983. Two such tests were conducted using the same equipment configuration (Figure 3.4). The tests involved pumping water from the 99.1 to 105.2 m depth of CR-11, and injecting water 10.6 m away into the 102.3 to 104 m interval of CR-6. Withdrawal rates were relatively constant over the duration of both tests, 11.84 L/hr (3.29×10^{-6} m^3s^{-1}) and 12.94 L/hr (3.59×10^{-6} m^3s^{-1}) for tests 1 and 2, as were injection rates, 9.67 L/hr (2.68×10^{-6} m^3s^{-1}) and 12.30 L/hr (3.42×10^{-6} m^3s^{-1}) for tests 1 and 2. The difference between injection and withdrawal rates was unintentional and resulted from errors in flow meter calibration. Both tests lasted approximately 30 hours and involved the injection of radioactive bromide (^{82}Br). Radioactive ^{85}Sr was added as a reactive tracer in the second tracer experiment. The flow field of the first test was analyzed using a numerical solution given by Bear (1979) to account for differences between injection and withdrawal flow rates while the second test was analyzed using an average flow rate in the GROVE model (modified from Grove and Beetem, 1971). Breakthrough concentrations were analyzed using a one-dimensional solute transport equation solution and summed over individual streamtubes. Both approaches yielded a longitudinal dispersivity of 1.4 m.

Raven (1986) described the results of five tracer tests conducted in a single fracture at the Chalk River site in 1985. Four of these tests were conducted in the same boreholes (designated as FS-6 and FS-15) while the fifth was conducted in FS-6 and FS-11. The layout of test boreholes and approximate extent of the fracture tested by Raven are shown in Figure 3.5. All but one test configuration corresponded to an injection withdrawal test, the exception being a radial convergent test. Table 3.4 summarizes the test conditions, including tracer, flow rates and borehole spacing, for the 1985 tests. Raven used two deterministic models, one a simple advection

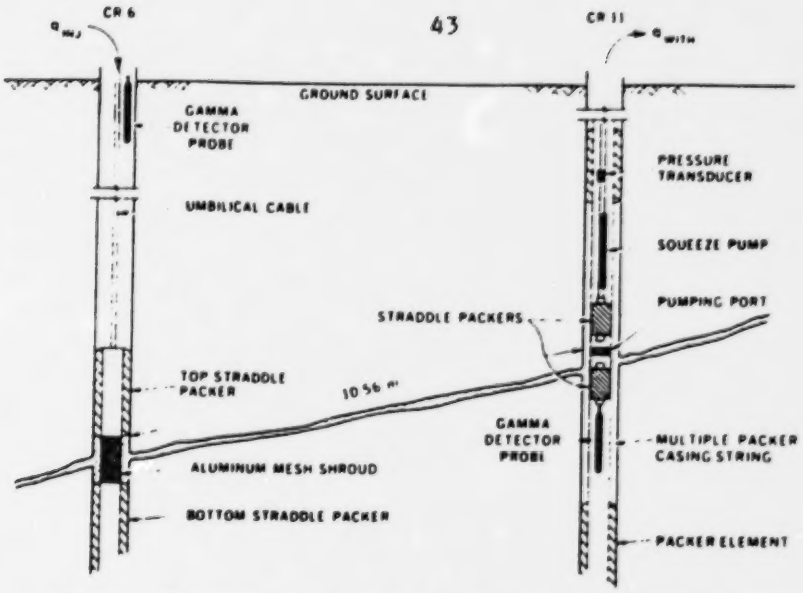

Figure 3.4 Schematic of borehole instrumentation used for injection-withdrawal tracer experiments (from Novakowski et al., 1985b)

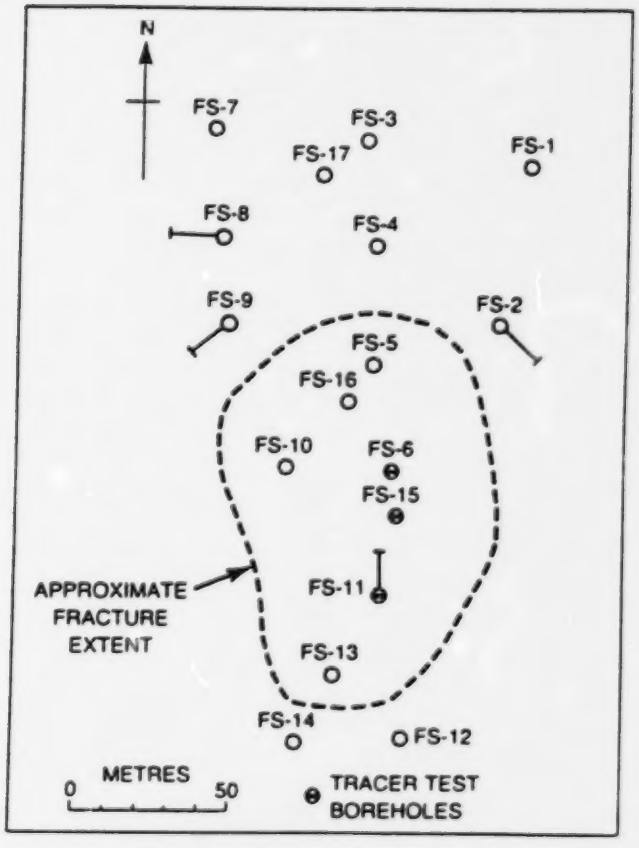

Figure 3.5 Borehole layout and approximate extent of fracture tested using tracers (from Raven, 1986)

INTERA

Table 3.4 Summary of Tracer Test Conditions (Raven, 1986)

Test	Tracer	Test Boreholes Injection	Test Boreholes Withdrawal	Flow Field	Borehole Spacing, m	M_{inj}	Q $L.h^{-1}$	ΔH m
1	^{82}Br	FS-6	FS-15	Inj.-With.	12.7	27 MBq	30.0	4.60
2	Na Fl.	FS-15	FS-6	Inj.-With.	12.7	100 mg	32.0	4.90
3	^{82}Br	FS-6	FS-15	Rad. Conv.	12.7	27 MBq	14.0	0.70
4	^{82}Br	FS-6	FS-15	Inj.-With.	12.7	40 MBq	36.6	2.35
5	^{82}Br	FS-6	FS-11	Inj.-With.	29.8	40 MBq	36.6	5.95

where: M_{inj} = mass of tracer injected as a slug

Q = withdrawal (injection) flow rate during test

ΔH = change in hydraulic head between injection and withdrawal boreholes during test

NaFl = sodium fluorocein (uranine)

dispersion (AD) model the other an advection dispersion with transient solute storage (ADTS) model, to fit residence time distribution (RTD) curves. The RTD curves basically consist of concentration distribution curves that have been normalized with respect to flow rate and total tracer injected. It was found that only the rising portion and the position of the peak of the field RTD could be fit using the AD model. The fits obtained through the use of the ADTS model (Villermaux and Van Swaaij, 1969) were significantly better, an observation which is likely attributable to the existence of two additional fitting parameters (N and ϕ) in the latter case. Table 3.5 presents the best fit dispersivity values for the five tracer tests. Using the normalized concentration (RTD) approach Raven (1986) was also able to develop a relationship for dispersivity as a function of velocity. This relationship (reproduced in Figure 2.3) would indicate the tendency of induced gradient tests to underestimate the natural dispersion occurring under the low hydraulic gradients present in most groundwater systems.

3.7 MISCELLANEOUS PROGRAMS

In addition to the tests associated with the major nuclear waste disposal programs a number of independent tests are worthy of note. These include tests conducted at the geothermal reservoir at Fenton Hill, New Mexico and the Massif Centrale in France.

The tests conducted in the geothermal reservoir at Fenton Hill are described in detail by Tester et al. (1982). These included a number of tracer tests in single and two well (injection-withdrawal) mode using a variety (^{82}Br, ^{131}I, dyes) of tracers. A number of the tests were analyzed using a simplistic one-dimensional solute transport model (based on residence time distribution (RTD) theory), while only one test was analyzed using a more sophisticated two dimensional analysis. The results of the one dimensional analysis were presented in terms of Peclet numbers which for the same flowpath should

Table 3.5 Summary of Best Fit AD and ADTS Model Parameters (Raven, 1986)

	AD Model Parameters			ADTS Model Parameters			
Test	2b μm	α_L m	ζ	2b μm	α_L m	N	ϕ
1	75	1.0	0.78	75	1.0	1.6	0.45
2	85	1.0	0.70	85	1.0	1.6	0.35
3	71	2.1	1.45	71	2.1	1.8	0.65
4	76	0.9	1.35	76	0.9	1.5	0.70
5	37	4.0	0.39	37	4.0	1.6	0.70

where: 2b = equivalent smooth parallel plate fracture opening;

α_L = longitudinal dispersivity

ζ = emperical fitting coefficient determined from ratio of theoretical and field RTD curves

N = dimensionless mass exchange constant describing rate of rate exchange between mobile and immobile fracture porosities

ϕ = mobile fracture of fracture pore space.

be relatively constant assuming that D is (as is typically assumed) a linear function of velocity. Unfortunately this was found not to be the case, and calibrated Peclet Numbers were found to vary from 0.89 to 5.12 for twelve tests. Tester et al. (1982) acknowledged this inconsistency and suggests that the existence of additional flow paths or a change in the character of flow in existing paths is the likely cause of the variations in Peclet Number. While it is conceivable that such an explanation may account for these observations, it is difficult to understand how a one-dimensional model could successfully reproduce the variable flow field resulting from different injection-withdrawal systems. Using a two dimensional analysis a 75-day step injection test was analyzed. This test yielded dispersivity values of 25 m and 50 m that included and excluded "formation dependent" effects respectively. This test, as for all tests, was conducted by injecting tracer at the 2760 m depth of well EE-1 and monitoring the response in well GT-2B at a distance of 100 m.

Robinson and Tester (1984) presented additional analyses of the injection-withdrawal tracer tests conducted at Fenton Hill, N.M. They indicated that dispersivities obtained from a one dimensional analysis using the advection-dispersion equation range from 15 m to 60 m. An approximate two dimensional method yielded dispersivity values of 5.4 m. One reason for the apparent difference in fitted dispersivity values between the one and two-dimensional analyses is that some of the observed dispersion in an injection-withdrawal tracer test results from the geometry of the flow field, and this geometry is only considered in the two-dimensional analysis. In addition, the generally lower dispersivity values reported by Robinson and Tester, as compared to those of Tester et al., result from the effects of tracer recirculation in the tests. Robinson and Tester (1984) accounted for the existence of recirculated tracer while Tester et al. (1982) did not.

Goblet et al. (1980) described three tracer tests conducted in the Massif Centrale between December 1976 and November 1977. The first of these tests were exploratory in nature and were not the object of any subsequent analysis. The second test involved pumping a centrally located well at a rate of 2.2 m^3/hr (6.11×10^{-4} m^3s^{-1}) for a fifteen day period. Four different tracers were injected in each of four surrounding wells. The wells were all approximately 40 m deep with the injection wells being located at distances of between 10 and 15 m from the pumping wells. The third test described by Goblet et al. (1980) was conducted in the same location as the second. This test involved pumping the same well at the same rate (2.2 m^3/hr or 6.11×10^{-4} m^3s^{-1}) over a slightly shorter period of time. Four tracers (strontium, cesium, Rhodamine WT, sodium iodide) were injected into a single well located some 12 m away. The results of the third tracer experiment were the only ones analyzed in detail. Goblet et al. (1980) used a two-dimensional numerical solution of the advection-dispersion equation to fit the breakthrough curves resulting from the pulse input of tracer. A single dispersivity value of 1.0 m was obtained from the analysis of these tests. Calmels et al. (1979) analyzed the same tests using a number of dimensionless curves (after Sauty, 1977) and obtained values of dispersivity ranging from 0.6 to 1.5 m. Insufficient information is given in these papers to discern the reasons for the difference between the two analyses. It is conceivable that the first analysis (Goblet et al., 1980) was performed with the intent of determining a single dispersivity value for all four injection points. Calmels et al. (1979) also analyzed some of the breakthrough curves corresponding to the earlier tests. They obtained dispersivity values of 4 m and 0.6 m corresponding to inter-well test distances of 11.35 m and 11.65 m, respectively. Calmels et al. (1979) also presented the results obtained from tracer experiments performed on cores. The cores contained a single fracture and averaged 4 cm in both length and diameter. Eight tracer experiments were conducted in total (four per core) with dispersivity values ranging from 8×10^{-4} m to 5×10^{-3} m for one core and 4×10^{-4} m to 4×10^{-3} m for the other. Again little discussion is given to possible explanations of the dispersivity differences.

The geothermal test site at Wairaki, New Zealand has also been the site of a tracer test. Horne and Rodriguez (1983) refered to Fossum and Horne (1982) as having obtained Peclet numbers ranging from 10 to 40 for a test at this location. No additional information is provided.

3.8 EVALUATION OF THE QUALITY OF DISPERSION PARAMETERS

This section contains an evaluation of the usefulness/appropriateness of the dispersion related parameters determined from various investigations.

Errors associated with dispersivity evaluations can typically be classified as either:

- errors associated with test analysis (e.g., insufficient knowledge of the hydrogeologic system being tested, inappropriate theory, mechanisms ignored, violation of assumptions);

- errors arising due to the test itself (e.g., borehole mixing and dilution effects, recirculation of tracer).

Before discussing the various sources of error that may exist for tracer tests, it is important to identify those conditions under which tracer tests will provide meaningful results. It is important, for example, that the percentage of the tracer mass recovery in an injection withdrawal or radial test be relatively high (i.e., greater than 50%). If the extrapolated mass recovered is less than this amount then it is doubtful that the system is sufficiently understood to warrant analysis of the data.

Assuming the results of the tracer test are such that the mass recovery criterion is satisfied, then the test should be analyzed using a model that accounts for all of the physical processes (or mechanisms) that may have existed during the test. An example of one such mechanism is matrix diffusion. Matrix diffusion effects are most significant for tests having low fluid velocities. Neglecting this mechanism under such low velocity conditions will result in an overestimation of the dispersion associated with the test. The analysis conducted by Webster et al. (1979) probably overestimated the dispersivity value of their test (134 m over 538 m distance) for this reason. Similarily, the analyses of the tracer experiments of Abelin et al. (1985) that neglect diffusion effects result in overestimation of dispersivity (see Table 3.1). The time frames of the Abelin et al. experiments (several hundreds of hours) require consideration of the effect of diffusion to a relatively immobile secondary porosity to yield meaningful estimates of dispersivity.

Other mechanisms which may have to be included in the test analysis are borehole dilution and mixing. Unless the test is configured so as to minimize the wellbore volume, the effect of borehole dilution should be incorporated into the analytical method. The effects of borehole mixing and dilution are generally important when either the volume of the borehole fluids or transit time of the tracer in the borehole is large relative to the same properties of the medium under test. Ignoring dilution and mixing mechanisms in boreholes and test equipment may result in anomalously high dispersivity values. This is probably one of the contributing factors to the high dispersivity values obtained by Tester et al. (1982) and may influence the reliability of the dispersivities reported by Leonhart et al. (1985) and Gelhar (1982). In the test of Tester et al., they pumped a pulse of tracer down a borehole to a depth of almost 3 km but apparently did not compensate for either the increased travel time or mixing along the borehole. Another factor which may contribute to the high dispersivity values obtained by Tester et al. (1982) (e.g.,

25 m to 50 m for an inter-well spacing of 100 m) may be the recirculation of tracer, the effect of which again was not considered. This fact coupled with the method of moment analysis technique employed by Tester et al. (1982) would tend to produce dispersivity values that are over estimated. In the experiments of Leonhart et al. and Gelhar, the residence time of tracer in the injection and withdrawal tubes approximates the residence time of tracer in the formation. This raises questions as to the reliability of the calculated dispersion parameters. The experimental dispersivities described by Cullen et al. (1985) are thought to be similarily compromised by the effects of borehole mixing at both the injection and withdrawal boreholes. Alternatively, several researchers (e.g., Novakowski et al., 1985b; Raven 1986) have designed their tracer experiments to minimize and quantify the effect of mixing in the boreholes.

This problem touches on another source of uncertainty in the analysis of tracer breakthrough curves which is the highly skewed nature of most breakthrough curves. A number of approaches have been proposed to fit the skewed nature of such curves. Some investigators use the concept of multiple flow paths to replicate the observed behavior. This approach, first proposed by Lenda and Zuber (1970), was used by Landstrom et al. (1983) and Gustafsson and Klockars (1981) in the analysis of their tracer tests. The major difficulty with such an approach is that little, if any, physical basis typically exists to justify the existence of the selected pathways. Another commonly employed method used to replicate the observed skewed behavior is through the introduction of additional transport mechanisms. This approach has been used by Moreno et al. (1983) in their attempts to duplicate field tracer tests conducted at Finnsjon. They used up to four parameters in their attempt to simulate the observed results. The danger in such an approach is the possible creation of mechanisms that have little physical basis. In this case, the model fitting becomes little more than an exercise in curve fitting and, since the quality of

the fit typically improves with the number of parameters, there may be a tendency to artificially increase the number of mechanisms. While such an approach may be perfectly valid provided the mechanisms are physically based and described accurately, this assumption should be verified by conducting multiple tests at the same location and only varying single parameters. Only then can the validity of the model be truly tested.

Attempts to duplicate the skewed nature of breakthrough curves using conventional solutions to the advection-dispersion equation or by the method of moments approach, typically results in extremely high dispersivity values being fitted since the data are biased by the long tails which occur. In extreme cases, the observed centre of mass of the breakthrough curve does not even approximately correspond to the plug flow travel time between injection and observation points determined using the advection-dispersion equation. The method of moments approach is subject to another source of error which arises from the skewed shape of the observed breakthrough curves. The long-tailed distributions render the results of an analysis especially sensitive to the detection limit or cut-off point used to terminate the distribution. Significantly different results may arise based on the selection of this variable.

Whatever the choice of analytical method, one should ensure that the method is both appropriate and solved correctly. A case in point is the analysis conducted by Davison (1982). He used the original formulation of the Grove model (Grove and Beetem, 1971) to obtain a dispersivity of 10 cm for a tracer test conducted over an inter-well distance of 12 m. This value is almost an order of magnitude lower than the value obtained by Novakowski et al. (1985a) and Lever (1984) for the same fracture but between different boreholes. The reason could be due to the analytical solution (proposed by

Brenner, 1962) contained in the original GROVE model. This solution is a one-dimensional solution to the advection-dispersive equation that assumes a boundary condition of C=0 at a distance equal to the inter-well spacing. As a result, the dispersive/diffusion flux entering the production wellbore is overestimated significantly due to the artifically high spatial concentration gradients imposed at the wellbore. To compensate for such an effect the contribution of other transport mechanisms (e.g., the dispersivity) would have to be reduced.

Table 3.1 includes a column which describes the reliability of tracer tests discussed herein. The tests have been described as being either reliable, unreliable or having insufficient information to formulate an evaluation. Generally, tests are judged to be reliable if the authors demonstrate a good understanding of the factors that may influence their test results and obtain values that seem reasonable (e.g., of same order of magnitude as tests conducted under similar conditions). These would include the results obtained by: Neretnieks et al. (1982), Landstrom et al. (1978, 1982, 1983), Gustafsson and Klockars (1981), Abelin et al. (1985), Leonhart et al. (1985), Novakowski et al. (1985), Raven (1986), Robinson and Tester (1984), Goblet et al. (1980) and Calmels et al. (1979). Tests that were judged to be unreliable were those where a potential problem is thought to exist (e.g., recirculation effects, borehole mixing and dilution, etc.). These would include the tests conducted by Webster et al. (1970), Davison (1982), Gelhar (1982), Raven and Novakowski (1984), Tester et al. (1982) and Leonhart et al. (1985). The remainder of the tests had insufficient information on which to judge the quality of the results and the reliability of the dispersion parameters from such tests are deemed uncertain.

The results of the tracer tests discussed in this report are summarized in Figure 3.4 as a log-log plot of longitudinal dispersivity (α_L) determined from each tracer experiment versus the distance (x) over which the parameter was measured. The data we identified as being reliable, uncertain or unreliable are based on previous discussion. Superimposed on this figure are lines of equal Peclet Number ($Pe = X/\alpha_L$). This plot is similar to Figure 2.5 from Lallemande-Barres and Peaudecerf (1978) who suggested a scale-dependence of dispersivity from their figure. The relationship for fractured crystalline rocks is generally less clear with groupings of dispersivity at low values (4×10^{-4} to 4×10^{-2} m) from laboratory experiments and at high values (0.4 to 7.8 m) from field experiments. It is clear however that all of the reliable (and most of the unreliable data) fall within Peclet Numbers of 1 to 100.

Neretnieks (1983) suggested that a constant Pe is characteristic of solute transport in rocks where significant channelling occurs. Under such conditions, the dispersivity is expected to increase proportionally to travel distance. Figure 3.4 at first glance, suggests that such a relation may exist. However, closer examination shows that two clusters of reported dispersivity values actually exist and that at large distances, the reported dispersivities are generally unreliable, in most instances being overestimated as a result of failure to include matrix diffusion, recirculation and borehole mixing effects. Figure 3.4 shows the largest reliable dispersivity measurement to be about 7.8, as reported by Landstrom et al. (1978). The constant Pe number interpretations of Figure 3.4 may also be inappropriate because of the relatively small and likely unrepresentative and disturbed samples of fractures tested in the laboratory experiments.

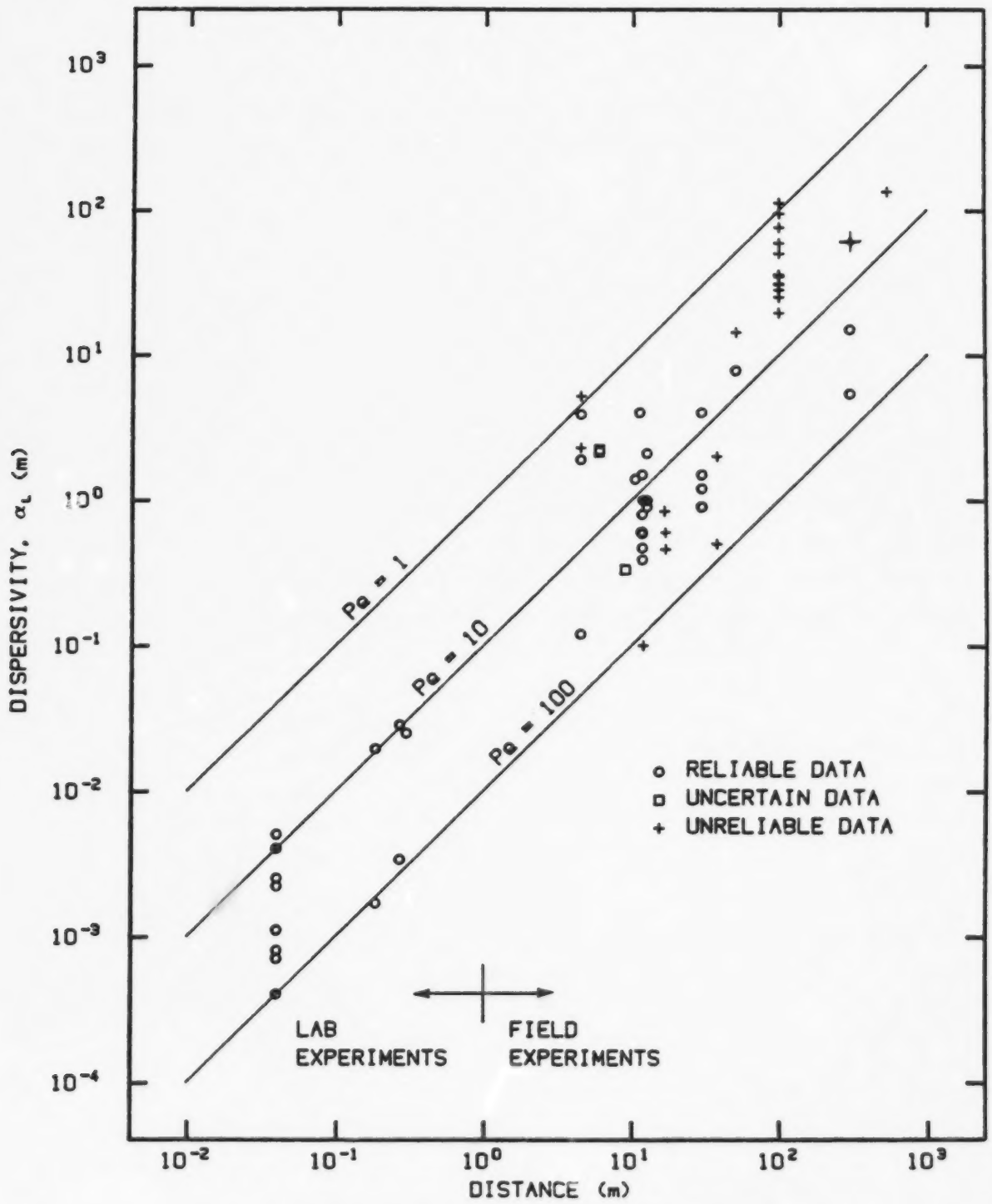

Figure 3.6 Longitudinal dispersivity from laboratory and field tests versus measurement distance

4. CONCLUSIONS

While it would appear that the Fickian approach to describing the dispersive process can adequately reproduce some observed solute transport behavior in fractured crystalline rock, it is also apparent that the dispersive process is still poorly understood. Many of the tests reported in the literature can be ruled unreliable because of incorrect analyses and/or poor test technique. Although the remainder of the tests may be reliable over intermediate test distances (10's of m), the data are largely inconclusive with regard to scale effects. Therefore, extrapolations to large spatial scales required for performance assessment of a nuclear waste repository, are largely unfounded. Furthermore, the existence of velocity-related effects may also complicate the extrapolation of existing test data to larger temporal scales. In summary, there is a clear need for well-controlled field tracer experiments in fractured crystalline rock over larger spatial and temporal scales than have been reported to date.

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GLOSSARY OF TERMS

Adsorption	The attachment of an aqueous chemical species to a solid. The attachment may be by an addition or replacment reaction. It may be either physical, designated by a low dependence of the rate of reaction on temperature, or chemical, designated by a high dependence of the rate on temperature.
Advection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with convection.
Anisotropic Medium	A porous medium having directionally dependent properties (e.g., hydraulic conductivity).
Aperture	A measure of the size of opening or silt representative of the void space of a fractured medium.
Aquifer	A formation containing sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Borehole Skin	A term developed in the petroleum literature describing a thin layer of material surrounding a borehole and possessing permeability different than that of the formation.
Brownian Motion	The irregular zigzag movement of extremely minute particles suspended in a liquid.
Capillarity	The property of tubes with hairlike openings when immersed in a fluid to raise (or depress) the fluid in the tubes above (or below) the surface of the fluid in which they are immersed.
Capillary Fringe	The zone immediately above the water table in which water is held above the water table by capillarity.
Compressibility	A material property describing the change in volume or strain induced in a material under an applied stress.
Conduction	Transmission through or by means of a conductor. Distinguished, in the case of energy, from advection and dispersion.
Confined Aquifer	An aquifer bounded above and below by impervious formations.

Consolidation	The process by which the volume occupied by solid porous medium reduces when the effective stress borne by the media increases.
Convection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with advection.
Diffusion	A molecular level process that spreads solute in water as a result of Brownian motion of water molecules.
Dispersion (Mechanical)	Refers to the velocity driven component of hydrodynamic and consists of the product of the groundwater velocity and a coefficient known as dispersivity.
Dispersivity	A coefficient used to relate mechanical dispersion to interstitial groundwater velocity.
Distribution Coefficient	A coefficient representing the partitioning of a groundwater contaminant between liquid and solid phases.
Effective Porosity	The amount of interconnected pore space available for fluid flow expressed as a ratio of interstical volume to total volume, also kinematic porosity.
Equilibrium	The state of a system that is thermodynamically the most stable at a given temperature, pressure, and elemental composition.
Equilibrium Water Saturation	The percent of water filled porosity corresponding to first appearance of a continuous water phase.
Evaporation	The net transfer of water from the liquid phase to the vapour phase.
Evapotranspiration	A combination of the evaporation and transpiration processes.
Fickian Transport or Process	Transport or flux of a solute as a result of Fick's law for molecular diffusion or an analogy applying Fick's law to processes other than diffusion.
Field Capacity	Water content remaining in a unit volume of soil after drainage resulting from gravity, does not represent an intrinsic soil property since gravity drainage continues indefinitely.

Flow Path Tortuosity	The nonstraight nature of soil pores.
Fracture System	A medium where the connected porosity transmitting groundwater is characterized as fractures or fissures.
Free Water Surface	The upper surface of groundwater or that level in the ground where the water is at atmospheric pressure; also water table; also phreatic surface.
Gradient	Change in dependent variable per unit change in spatial or temporal independent variable.
Gravitational Potential	The difference in elevation between the point of interest and a reference point or plane.
Hydration	The process of clustering ions of unlike charge and incorporating water molecules in loosely bound complexes.
Hydraulic Conductivity	The proportionality factor in Darcy's law as applied to the viscous flow of water in soil (i.e., the flux of water per unit gradient of hydraulic potential).
Hydrodynamic Dispersion	The process by which solute spreading occurs on a macroscopic scale due to mechanical and molecular mixing.
Hysteresis	The loop in the moisture content versus matric potential curve defined by the retention (drying) and imbibition (wetting) curves.
Imbibition	To wet or imbibe the soil profile.
Immiscible Displacement	Displacement of one fluid by another.
Infiltration	The downward entry of water into the soil.
Intrinsic Permeability	The property of a rock or soil defining its ability to transmit a fluid.
Ion Exchange	The process of exchanging two ions on an adsorption site.
Isotropic	Independent of direction, used to describe properties of the porous medium (e.g., hydraulic conductivity).

Kinematic Pathline	The path of solute in an aquifer that is determined strictly by the pore water path and velocity.
Kinematic Porosity	The volume of flowing water per unit bulk volume of porous medium, also effective porosity.
Kinetics	A term to designate dynamic chemical changes toward the state of chemical equilibrium.
Mass Flux	Rate of transfer of mass across a surface.
Nonequilibrium	A state of a system that is not thermodynamically the most stable.
Peclet Number	A nondimensional quantity defining the relative importance of advection in comparison to diffusion or diffusion-type dispersion.
Pellicular Water	Water adhering as films to the surfaces of openings and occurring as wedge-shaped bodies at junctures of interstices in the zone of aeration above the capillary fringe.
Permeability	see intrinsic permeability.
Phreatic Aquifer	An aquifer bounded below by an impermeable formation and above by the free water surface.
Pluton	A body of igneous rock that has formed beneath the surface of the earth by consolidation from magma.
Pore	An interstice or void. A space in rock or soil not occupied by solid mineral matter.
Porosity	The ratio of the volume of voids to the total volume of porous media.
Porous Media, Medium	A physical environment containing voids, pores, interstices, or other openings that may or may not interconnect.
Potentiometric Head	The height of a surface to which water in an aquifer would rise by hydrostatic pressure.
Reactive Solute	A solute that reacts with the medium by any of a number of processes.
Recharge	The quantity of water or the process by which water is added to the zone of saturation.

Relative Saturation	The ratio of water-filled pore volume to total pore volume.
Retardation Factor	The reciprocal of the retarded solute velocity of the groundwater (i.e., reciprocal of relative velocity).
Saturation (water)	The total water that can be absorbed by water-bearing materials without dilation of the sediments.
Soil Matrix	The unconsolidated mineral material comprising a major portion of, if not the entire, vadose zone.
Soil Water Potential	The amount of work a unit quantity of water in an equilibrium soil-water system is capable of doing when it moves to a pool of water in the reference state of the same temperature.
Solute	The chemical species appearing as a dissolved constituent in soil water or groundwater.
Specific Retention	The volume of water per unit area of soil retained by a soil column.
Specific Storage	The volume of water that a unit volume of a formation releases from storage due to a unit decline in head.
Specific Yield	The volume of water per unit area of soil released by a soil column, extending from land surface to free water surface, when the water table is lowered one unit depth.
Storativity	The volume of water that a unit area of an aquifer releases from storage for a unit decline in head.
Thermal expansivity	A material property describing the volumetric change resulting from changes in temperature.
Transmissivity	The flow of water through a unit width of aquifer under a hydraulic gradient of one equal to the product of hydraulic conductivity and aquifer thickness (for a saturated confined aquifer).
Transpiration	The process by which plants remove moisture from the soil and release it to the atmosphere as vapour.

Unsaturated System	That portion of the subsurface geology where the porosity is shared by water and air, and the matric potential is nonzero (i.e., the water content of the soil profile is less than saturation).
Vadose Water	Water in excess of pellicular water seeping toward the water table; used in this text as a synonym for gravity water.
Viscosity, Coefficient of	The amount of force necessary to maintain a unit difference in velocity between two layers of water a unit distance apart.
Void Ratio	Ratio of void volume to solid volume.
Water Table	In pervious granular material the water table is the upper surface of the body of free water which completely fills all openings in material sufficiently pervious to permit percolation. In fractured impervious rocks and in solution openings it is the surface at the contact between the water body in the openings and the overlying ground air.